Before the
Federal Communications Commission
Washington, DC 20554

In the Matter of	)	
	)	
Spectrum Horizons	)	**ET Docket No. 18-21**

To: The Commission

COMMENTS OF PROFESSOR DANIEL MITTLEMAN

1. These Comments are submitted by Daniel Mittleman, a Professor in the School of Engineering at Brown University in Providence, Rhode Island. For over 20 years, my area of specialization has been the science and technology of sub-millimeter and terahertz waves and their uses in spectroscopy, imaging, and sensing.[1] I feel very strongly that this region of the spectrum is poised to have an enormous economic impact. There has been rapid technological progress in the field, along with an astounding acceleration in recent interest on the part of many companies, both in the United States and abroad. Use of frequencies above 95 GHz is no longer just a hope for the future. Moreover, my experimental work has shown that some commonly-held beliefs about limited propagation characteristics are invalid. It is time now for the FCC to take the lead in opening the doors to the benefits of the new technology.

2. The impact of submillimeter technology will be felt in many different areas. One prominent example is the area of wireless communications, including providing broadband service to locations where optical fiber is impractical; however, many other examples are in the works, with some already in commercial deployment. I am submitting this comment to provide my perspective about the technological areas in which submillimeter or terahertz waves will play a critical role in the near future. It is my hope that these considerations will inform the FCC's

[1] I am currently studying the propagation characteristics of radio waves above 95 GHz under call sign WI2XVS.

future decisions regarding this fruitful region of the electromagnetic spectrum.

3. One key concern is in the area of future wireless technologies. It is clear that there is an upper limit to the data transfer rates on existing networks, and that we are rapidly reaching that limit. It is also clear that demands for wireless bandwidth will continue to grow exponentially for at least the next several years (if not longer). This confluence of events will, without any doubt, overwhelm the capacity of existing network infrastructure. Even millimeter-wave bands below 95 GHz will eventually be unable to handle this accelerating demand for bandwidth. One solution that is gaining favor among researchers, as well as groups such as the IEEE 802.15 WPAN Terahertz Interest Group (IGTHz), is the idea of developing new network capabilities, not to replace but to supplement the existing cellular architecture. These new capabilities would rely on a higher carrier frequency, with a shorter range but massive (by current standards) bandwidth for high-data-rate transmission. Modeling and measurements both indicate that various bands within the 100 GHz – 1 THz range can be used in such applications, for backhaul between small cells, as well as for bursty download links. This range of frequencies is simply better suited to transporting large data than the already over-utilized frequencies in the 1-5 GHz range. Routing such data to a terahertz layer would provide the opportunity to return much of the existing cellular spectrum currently tied up with data delivery back to enhance the capacity of voice services. These frequencies would coexist and not interfere with the existing cellular and Wi-Fi infrastructure. Crucially, because of the shorter propagation distances, the narrowly focused beams that are readily achieved at these frequencies due to their small wavelength, and the opacity of most materials, these services would also not interfere with passive applications such as earth observing or astronomy, *even in outdoor implementations*. Clearly, many uses of these frequencies will involve indoor applications that would be blocked by building materials from interfering with passive users. Yet, others will involve outdoor

applications where such interference could be a concern. However, these concerns can be addressed; for example, beam patterns could be restricted to low elevation angles in order to avoid impacting passive users. This would be completely effective for protecting astronomical observatories (where the receivers mostly point up, not sideways) as well as earth-observing satellites (where the long atmospheric path length for a horizontally oriented transmission would protect limb-sounding receivers from any interference).

4. Evidently, fiber optics technology is cross-elastic for some of the envisioned communications applications, and has low hardware cost today. However, there are many obvious situations in which a wireless link is preferred or required. Moreover, fiber optic technology has highly variable installation costs that can dominate in certain applications such as unexpected needs in highly urbanized areas. In such cases radio system can be installed much faster and at much lower costs even though optical systems are less expensive generally. In the special case of restoring communications networks after a major catastrophe these radio systems fill a niche with no other viable alternative. Finally, radio systems have an intrinsic time latency advantage of about 30% due to the lower index of refraction of air versus the glass material in fiber optics. The explosive growth of worldwide wireless traffic speaks for itself; the world needs more bandwidth.

5. In addition to this vision for future wireless data services, a host of other applications using the same spectral range are already in development, or in deployed use. Low-power short range terahertz systems are already being used in commercial settings for sensing, imaging, package inspection, security, and quality control, in a variety of manufacturing and process environments, both in the US and overseas, as well as in many basic scientific studies involving spectroscopy and imaging. This technology space already includes a number of companies in the US, both large and small, who sell systems that use terahertz radiation, and their number is

growing. The ongoing advances in terahertz technologies, including rapid developments in silicon CMOS-based solutions, quantum cascade lasers, and terahertz and sub-millimeter-wave components, will continue to accelerate these trends. All of this effort is driven by compelling needs. There are many sensing and imaging tasks for which radiation in this spectral range is simply the only solution; in other cases, terahertz imaging systems may provide a more cost-effective or less hazardous alternative to other more conventional technologies such as x-ray imaging or beta gauges. Clearly, issues of regulation and spectrum allocation will have a significant impact on US competitiveness in this burgeoning technology space.

6. In this context, it is important to point out the vast diversity of sources and systems that currently operate in the terahertz range. For example, commercial terahertz time-domain spectroscopy systems produce low-power (typically -30 dBm) extremely broadband (continuous frequency coverage from 100 GHz to several THz) trains of pulses. In contrast, typical electronic sources based on frequency multipliers might produce up to several dBm of power, in a continuous (not pulsed) beam, with a bandwidth of only a few MHz or less. Photomixing sources typically provide narrowband (MHz) output, but with continuous tunability over the range from 100-1000 GHz, while THz gas lasers operate at only a few fixed (not tunable) frequencies. These are only a few examples, to illustrate the point: it will be challenging to develop rules and standards to cover issues such as exposure and interference which can be uniformly applied to all of these situations. FCC must consider this vast diversity carefully in future deliberations, in order to avoid placing an unreasonable burden on any one method for accessing the THz range.

7. The goals for this technology are not merely “pie in the sky” visions of a few academics. For example, Figure 1 shows a summary of recent research results (as of late 2016) from terahertz wireless communications test beds around the world. This plot, adapted from

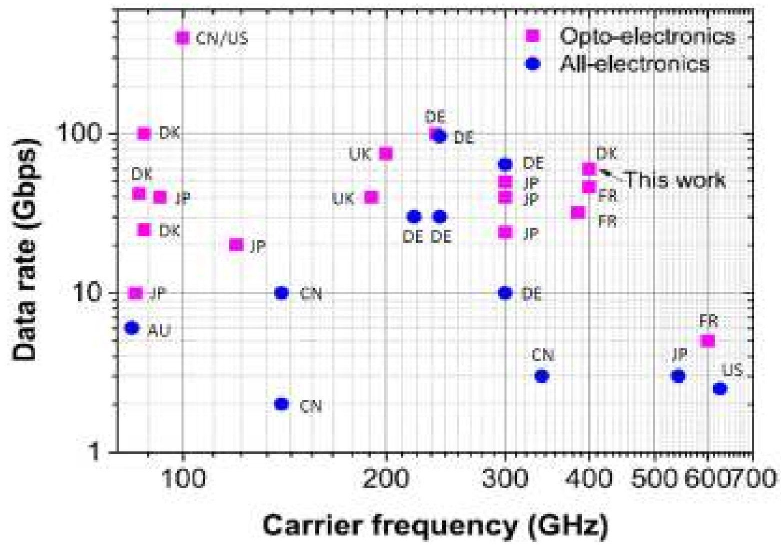

Figure 1 – A summary of all of the recent experimental demonstrations of terahertz wireless links (as of late 2016), plotted to indicate the achieved data rate and carrier frequency used in each experiment. Each data point is labeled according to the nationality of the authors. The point labeled "this work" refers to reference [2], from which this plot was adapted with the assistance of its authors. Note that only two of these data points include co-authors from the US.

reference 2, convincingly demonstrates two facts: (a) the field of terahertz wireless communication research is active and growing, with rapid progress in the development of tools and systems that can solve real-world problems; and (b) essentially all of this research is happening outside of the US. This second fact is alarming, because US leadership in wireless technology is at risk, as is the enormous economic benefit that has resulted from that leadership. Our competitors around the world are running ahead in this technology arena. If we remain passive, then by the time these networks are ready for commercial deployment, the US will no longer be the world's leader, and the majority of the economic impact will flow elsewhere.

8. Figure 1 represents one example illustrating the explosive growth in the terahertz field in recent years, and the tremendous potential perceived by research communities around the world. A second result comes from one of my own publications,[3] shown in Figure 2. As in Figure 1, most of the data point in the upper part of this plot, with the exception of the points

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[2] X. Yu, *et al.*, *IEEE Transactions on THz Science and Technology*, **6**, 765 (2016).
[3] J. Ma, R. Shrestha, L. Moeller, and D. M. Mittleman, *APL Photonics*, **3**, 051601 (2018).

circled in red, represent data acquired by groups outside of the US. The messages here are clear: (1) high data rates can realistically be achieved over reasonable distances, both indoor and outdoor; and (2) the US is rapidly falling behind the rest of the world. With respect to this latter problem, it is not much of a stretch to suggest that a lack of leadership from the federal agencies who are responsible for fostering innovation in wireless technology is a contributing factor.

9. Even in the area of safety regulation, the US has fallen behind. To give an example,

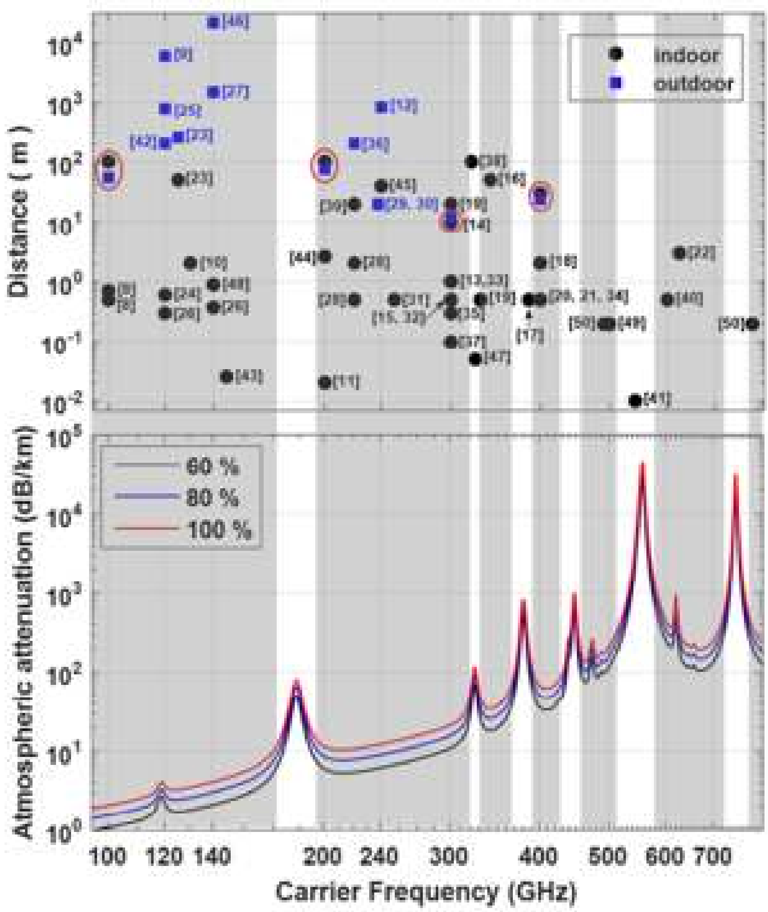

Figure 2 – (Top) Distance versus carrier frequency obtained for indoor and outdoor wireless communication systems. The numbers in brackets indicate the literature reference from which the data point was taken; reference list can be found in [3]. The data points circled in red indicate the results from Prof. Mittleman's laboratory at Brown University. (Bottom) Impact of atmospheric attenuation of THz waves under different humidity with humidity from 60% to 100%.

the EU has had RF safety limits in place for frequencies up to 300 GHz since 1999,[4] whereas FCC has yet to even offer a proposal for above 100 GHz.

10. I must continue to emphasize the important role played by the FCC in the future growth of this technology in the US. A lack of clarity in the processes for spectrum allocation and the rules regarding sale and use of terahertz equipment undoubtedly inhibits innovation and commercial growth. What company would want to invest in the development of a new technology if they know that FCC will deny them the right to use it? Indeed, any absolute prohibition on spectrum sharing definitely discourages R&D in these spectral bands. Moreover, such prohibitions would be illogical, since they are based on notions of interference that may apply well to lower frequency bands, but that often do not apply at all at these higher frequencies. In fact, sharing spectrum without interference is substantially *easier* at higher frequencies, for several reasons. These include: (a) the atmosphere attenuates signals more rapidly as frequency increases (aside from narrow molecular resonances); (b) building materials are almost completely opaque; (c) beams are highly directional, often with very small side lobes which can be easily shielded. Obviously, all of these statements can be quantified.

11. Decisions on spectrum sharing should be well-informed and based on these quantifiable results that are explicitly related to frequencies above 100 GHz, not based on incorrect assumptions that rely on information relevant only to lower frequencies. This has not always been the case. For example, an existing footnote to the US spectrum allocation table (US246) places anachronistic and unreasonable limits on emissions up to 250 GHz. This regulation makes no sense, and must be updated. Rather than adopting rules that simply prohibit all emissions in a given band, perhaps it would be possible to adopt the ITU-R RS.2017

[4] *See*: Council Recommendation on the Limitation of Exposure of the General Public to Electromagnetic Fields (0 Hz to 300 GHz), 1995/519/EC, July 12, 1999, at: https://ec.europa.eu/health/sites/health/files/electromagnetic_fields/docs/emf_rec519_en.pdf.

recommendations in order to limit the power reaching a satellite (it is quite likely that the only realistic interference issue involves downward-looking satellites). A limit like that, which limits the power reaching a sensitive receiver rather than the power broadcast by the transmitter, would place specific requirements on maximum transmitter angle and side lobe emission. These limits would probably be relatively easy to satisfy, in most cases, without compromising the desirable capabilities of the transmitter. This suggested approach would be just as effective in avoiding interference as a complete ban on sharing. But, it would encourage, rather than inhibit, innovation and economic development. For example, it would encourage research on antennas that have low gain at high angles. There's no motivation to develop these while US246 remains in force. That's just one example; there are many others.

12. In that context, it is also worth noting that there is quite a bit of misinformation about the characteristics of millimeter-wave and terahertz signals, even in the recent peer-reviewed literature. Speaking from personal experience, I have been told by 'experts' that terahertz beams cannot propagate for more than a few meters in air, despite many published examples to the contrary (e.g., Figure 2). I have been told that outdoor THz links are impossible over any range greater than a few meters, because of atmospheric turbulence. I have been told that rain adds many tens of dB of attenuation to the link budget for a 100-meter THz link. Even more often, I have been told that THz links can only support direct line-of-sight channels in realistic scenarios. All of these claims are based on 'conventional wisdom,' and all are wrong, proven so by experiments; please see Figure 3 for a counter-example from my own research group. It is critically important that the FCC's deliberations be informed by the best and most accurate available science, and not by conventional wisdom, which appears to be often unreliable.

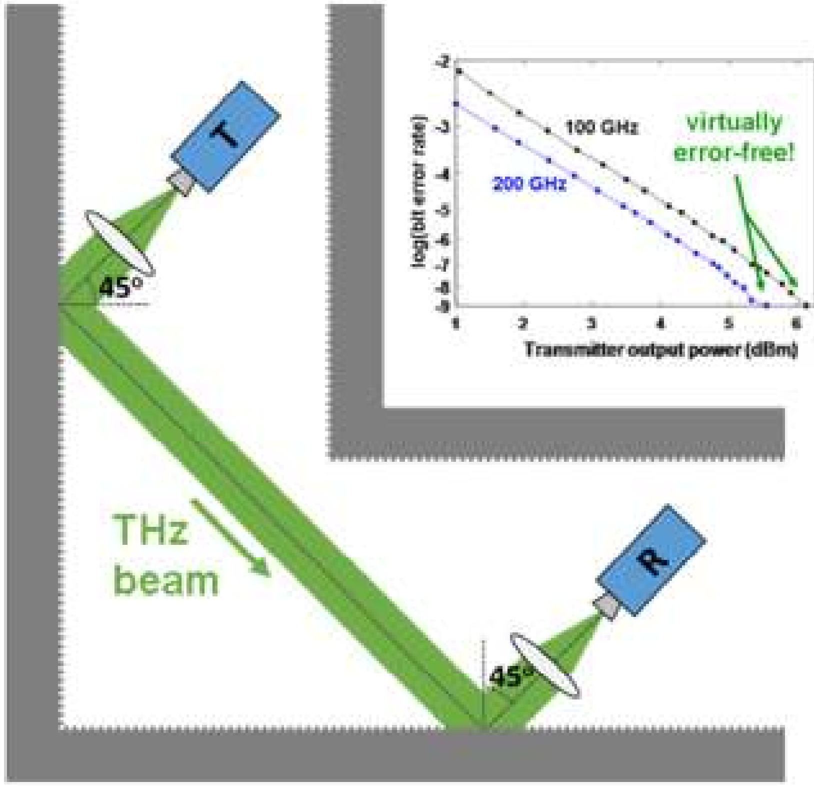

Figure 3 – A schematic illustration of a terahertz wireless data link, where the transmitter and receiver are not visible to each other by line of sight. The link is completed by two bounces off of an ordinary unmodified painted cinderblock wall. The inset shows measured bit error rates vs. the output power of the transmitter, at 100 and 200 GHz, demonstrating that such non-direct links are feasible. From [3].

13. The situation described here is stifling innovation in the US. Even in the academic world, we are substantially impacted by the uncertainty in the existing regulatory structure. For example, my own efforts to initiate a federally funded research center on this topic will only be successful with the active participation of companies who stand to benefit from research collaborations, technology transfer, and access to a pool of trained students. Yet, many companies may be reluctant to put resources into such collaborations when they perceive regulatory roadblocks which would inhibit their future ability to exploit the fruits of those labors. In addition, federal funding agencies are not apt to take THz communications seriously if they see that the FCC is adversarial to such ideas, rather than supportive of them. The impact of FCC's decisions are widespread.

14. I urge the FCC to carefully consider all of the envisioned uses of these technologies in your deliberations, as well as the most accurate and recent research results. Please do not rely on conventional wisdom, because the conventional wisdom for 3 GHz may not be so wise at 300 GHz. My strong opinion is that technologies which exploit terahertz and millimeter waves are poised to have a significant economic impact in the near future, creating jobs and stoking innovation in the US. Federal agencies such as FCC are in a position to foster this emerging area, to help restore and maintain our nation's competitive position.

15. I am at the Commission's disposal as a resource for further information or discussions.

Respectfully submitted,

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